ThB2.1 (Invited)
11:00 am – 11:30 am

GROWTH AND DEVICE PERFORMANCE OF InP/GaAsSb HBTS

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Abstract

We report the growth of high-quality InP/GaAsSb heterojunction bipolar transistors (HBTs) for high-frequency applications by metalorganic vapor phase epitaxy (MOVPE) and gas-source molecular beam epitaxy (GSMBE) using carbon as a base dopant. Hole concentrations above 10^{20} cm^{-3} are achieved in a carbon-doped GaAsSb base layer. We measure type I and type II luminescence from InP/GaAsSb/InAlAs and GaAsSb/InP superlattices to evaluate quickly the HBT's GaAsSb base layer and collector-base and base-emitter heterojunction quality. The HBTs exhibit excellent DC characteristics and a current gain cutoff frequency over 210 GHz.

I. Introduction

While InP/InGaAs-based heterojunction bipolar transistors (HBTs) have shown excellent microwave characteristics [1], [2], the collector design is complicated due to a current blocking problem resulting from the type I band alignment, and consequent barrier to electron collection, between $In_{0.53}Ga_{0.47}As$ and InP [3], [4]. InP/GaAsSb HBTs have recently attracted much attention [5], [6] because the type II (staggered) band alignment of this heterostructure provides a solution to the collector current blocking problem common to HBT designs based on the InP/ InGaAs heterostructure. At room temperature, the conduction band energy of $GaAs_{0.51}Sb_{0.49}$ is ~0.15 eV higher than that of InP [7], [8], enabling the realization of an abrupt collector-base heterojunction without collector current blocking. InP/GaAsSb HBTs have demonstrated excellent DC and microwave characteristics suitable for high-frequency applications. In this work, we report the growth of high-quality InP/GaAsSb HBTs with carbon as a base dopant by metalorganic vapor phase epitaxy (MOVPE) and gas-source molecular beam epitaxy (GSMBE). We discuss the growth characteristics and material properties of MOVPE- and GSMBE-grown carbon-doped GaAsSb layers. To evaluate quickly the HBT's GaAsSb base layer and collector-base and base-emitter heterojunction quality, which are critical to the device performance, we measure luminescence from InP/GaAsSb/InAlAs and GaAsSb/InP superlattices (SLs). We also present DC and microwave device performance of the HBTs.

II. Experimental

Epitaxial layers were grown both by MOVPE and GSMBE. For MOVPE growth, we use a home-built reactor with configuration and growth conditions as described below. For MBE growth, we use a modified Varian Modular Gen II GSMBE system with configuration and growth conditions as described below. All growths are done on semi-insulating (100)-oriented InP substrates.

The vertical MOVPE reactor is equipped with a close-coupled showerhead injector, fast-switching valves, pressure-balanced run/vent manifold, and in situ normal-incidence reflectometer. The reactor is typically operated at 76 Torr with a total H_2 flow of ~10 slm, a substrate rotation of 120 rpm, and growth temperatures of 580–620 °C. The growth temperature is controlled by resistive heating and is measured by a thermocouple calibrated using the 575 °C eutectic temperature of $AlSi_x$. TMAl, TEGa, TMIn, TMSb, AsH_3 and PH_3 are used as precursors. Ditertiarybutylsilane and disilane are used for n-type doping and CBr_4 is used for p-type doping. The growth rates for InP and undoped GaAsSb are 1.2 µm/h and 1.4 µm/h, respectively.

The MBE system is a modified Varian Modular Gen II GSMBE system equipped with standard high temperature effusion cells for Al, Ga, and In, a high-temperature hydride cracker for creating As_2 and P_2 from AsH_3 and PH_3, and an EPI solid Sb cracker providing Sb_2. The n-type dopant is Si from elemental Si in a high-temperature effusion cell. CBr_4 from a low-temperature gas injector is used for p-type doping. The growths are performed in a temperature range of 480-500 °C as measured by an IR pyrometer. Typical growth rates are 0.6 µm/h for InP and 0.5 µm/h for GaAsSb. A cryopump and liquid nitrogen cryopanels are used to maintain the growth chamber pressure below 1×10^{-5} Torr during growth.

III. Results and Discussion

The very high solubility and low diffusion coefficient of carbon [9], [10] make it an ideal p-type dopant for the GaAsSb base layer in InP/GaAsSb HBTs where high doping concentration and an abrupt doping profile in the base layer are highly desirable. Fig. 1 shows the room temperature hole mobilities for MOVPE- (open circles) and GSMBE-grown (solid squares) carbon-doped GaAsSb as a function of the hole

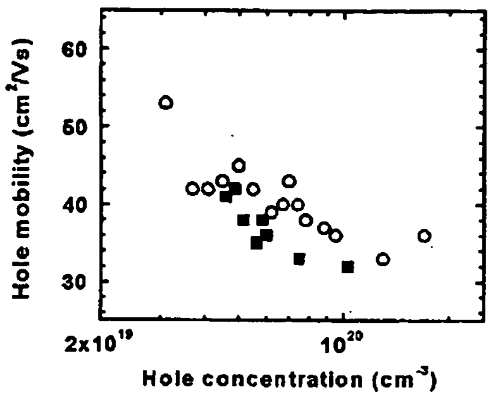

Fig. 1 Room temperature hole mobility as a function of carrier concentration in MOVPE- (open circles) and GSMBE-grown (solid squares) carbon-doped GaAsSb.

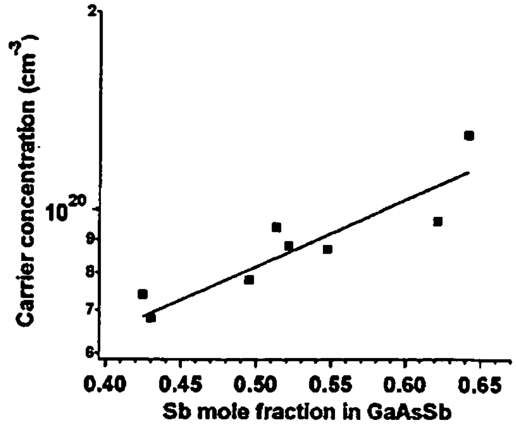

Fig. 2 Hole concentration dependence on Sb mole fraction in MOVPE-grown GaAsSb.

concentration. Hall measurements were carried out using the standard van der Pauw method. Undoped GaAsSb is p-type with a background carrier concentration of ~6×10^{16} cm^{-3} and a mobility of ~ 74 cm^2/Vs, similar to results reported by others [11], [12]. The hole concentrations up to 1.7×10^{20} cm^{-3} were achieved in MOVPE-grown GaAsSb. The mobilities drop from ~43 cm^2/Vs to ~33 cm^2/Vs as the hole concentrations increase from ~5×10^{19} cm^{-3} to ~1×10^{20} cm^{-3}, showing the weak dependence on the doping level. Previous reports on the hole mobilities for the heavily doped GaAsSb samples were in the range of 30–40 cm^2/Vs and low mobilities were attributed to strong alloy scattering in GaAsSb [13], [14]. As seen in Fig. 1, the hole mobilities of MOVPE-grown GaAsSb are somewhat higher than those of GSMBE-grown GaAsSb. GaAsSb is known to order compositionally when grown epitaxially and the surface reconstruction is believed to be a key factor in the ordering process [15]–[17]. The difference in the degree of ordering between the MOVPE- and GSMBE-grown samples resulting from different growth conditions such as growth temperature and precursors may be responsible for somewhat lower mobility values found in the GSMBE-grown samples. Similar to CCl_4 doping of InGaAs and AlGaAs [18], [19], CBr_4 doping shows strong effects on the growth rate and layer composition of the MOVPE-grown GaAsSb. The growth rate for heavily doped layers was reduced to 2 Å/sec, compared to 4 Å/sec for undoped layers, most likely due to the formation of volatile $GaBr_x$ species. The addition of CBr_4 shifted the composition of GaAsSb to As-rich and it was necessary to adjust the AsH_3 flow to maintain lattice-match for each change in carbon doping level. Interestingly, CBr_4 doping has no such effect in the GSMBE-grown GaAsSb. Although further investigation is necessary to understand such behavior, the fact that CBr_4 is pre-cracked in GSMBE while it decomposes near the growth surface in MOVPE may play an important role. For the MOVPE-grown GaAsSb, carbon incorporation was found to increase with decreasing growth temperature, similar to trends reported for GaAs [9].

Hydrogen passivation of the carbon acceptors has been shown to be a significant problem for InGaAs and GaAs at high carbon doping levels [18], [20]. No measurable hydrogen passivation effect was detected in heavily doped GaAsSb, in agreement with previous reports [11], [12], [21]. The Hall measurements after post-growth annealing at 450 °C for 5 min. under nitrogen yielded hole concentrations at approximately the same level. Bhat et al. reported that electrochemical C-V measurements consistently gave higher hole concentration values than those obtained by Hall measurements, with a discrepancy varying from about 2× to 8× as the doping level increased from about 10^{18} to 7×10^{19} cm^{-3} for MOVPE-grown GaAsSb [21]. This discrepancy was attributed partly to the presence in the GaAsSb of a large number of acceptor-like deep levels, which are expected to not to be ionized at room temperature. However, unlike the previous report, the discrepancy between Hall and electrochemical C-V measurements was only 15–35 % for our GaAsSb samples at the doping levels of 5×10^{19}–1×10^{20} cm^{-3}.

Fig. 2 shows the effect of varying Sb mole fraction on hole concentration for the MOVPE-grown GaAsSb samples. The samples were grown at 580 °C with a fixed CBr_4 flow. As the Sb mole fraction increases from 43 to 64 %, the carbon incorporation efficiency increases by a factor of ~2. It should be noted that we could only obtain the high carrier concentrations (≥ 10^{20} cm^{-3}) with the Sb-rich condition (under compressed strain). Watkins et al. observed a similar trend in CCl_4 doping of MOVPE-grown GaAsSb and they attributed this trend to an increase in the solubility of the acceptor over the zero strain limit due to the large difference in atomic radius between Sb and C [14]. However, in the case of

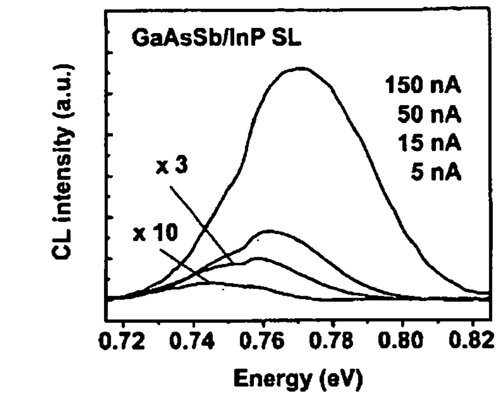

Fig. 3 CL spectra of a GaAsSb/InP SL measured at 4.2 K with various electron beam excitation currents.

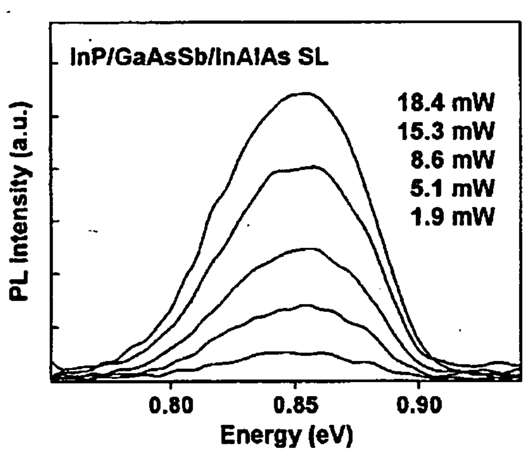

Fig. 4 PL spectra of a InP/GaAsSb/InAlAs SL measured at 8.5 K with various laser excitation powers.

GSMBE-grown GaAsSb samples, the doping level of ~1 × 10^{20} cm^{-3} was achieved on the near lattice-matching condition; clearly, further investigation is needed to see whether this behavior is related to the inherent difference in growth kinetics between MOVPE and MBE.

One of the key device performance parameters in HBTs is the current gain, which is determined both by the quality of the GaAsSb base layer and of the base-emitter heterojunction. In addition, collector leakage will be adversely impacted by a low-quality collector-base heterojunction. So in general, non-radiative recombination due either to bulk or interface defects in the GaAsSb and at the heterojunctions should be minimized. To evaluate quickly these material growth issues, we measure luminescence from GaAsSb/InP and InP/GaAsSb/InAlAs SLs for HBTs with an InP or InAlAs emitter. Fig. 3 shows the low-temperature cathodo-

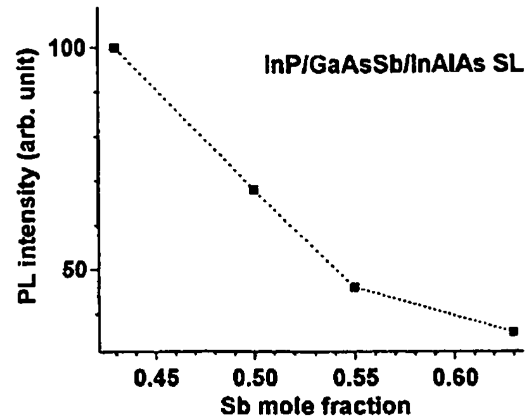

Fig. 5 Room temperature PL intensity dependence on Sb mole fraction in InP/GaAsSb/InAlAs SLs.

luminescence (CL) spectra of a MOVPE-grown 7-period GaAsSb/InP (70 Å/250 Å) SL. The CL peak from GaAsSb/InP SL shows a large blue-shift with an increase in an electron beam excitation current and is assigned to spatially indirect type II recombination between electrons in the conduction band of InP and holes in the valence band of GaAsSb. We have reported detailed studies on structural and optical properties of GaAsSb/InP SLs elsewhere [22]. Direct observation of strong type II luminescence is indicative of the high-quality GaAsSb/InP heterojunctions.

Fig. 4 shows the low-temperature photoluminescence spectra of a GSMBE-grown 7-period InP/GaAsSb/InAlAs SL (15 Å/70 Å/250 Å). The InP/GaAsSb/InAlAs SL exhibits much higher luminescence peak energy than the GaAsSb/InP SL. In contrast to the large blue-shift observed in the GaAsSb/InP SL, which is peculiar to type II recombination, the shift in CL peak energy is less than 5 meV/decade with no noticeable peak broadening when increasing the laser power. These spectral features are similar to those observed in GaAsSb/InAlAs SLs [22], which have type I band alignment. Thus, the PL peak from an InP/GaAsSb/InAlAs SL is assigned to spatially direct type I luminescence within GaAsSb. Fig. 5 illustrates the effect of Sb mole fraction on the room temperature PL intensity of MOVPE-grown InP/GaAsSb/InAlAs SLs. As the Sb composition increases from 43 to 63 %, the PL intensity drops more than a factor of 2. Although we cannot rule out the negative effects of misfit strain, the PL intensity drop is most likely related to an increase in the doping level with Sb mole fraction as seen in Fig. 2, which sharply increases non-radiative recombination such as Auger recombination.

Typical HBT structures include a 1500–3000 Å InP collector Si-doped at 2–3 × 10^{16} cm^{-3}, 300–500 Å carbon-doped GaAsSb base (700–1200 Ω/sq.), Si-doped InP or InAlAs emitter, and 400 Å InGaAs emitter contact layer Si-doped at 2 × 10^{19} cm^{-3}. The HBTs are a self-aligned, emitter-up triple mesa structure with Si_3N_4-passivated mesa walls. The

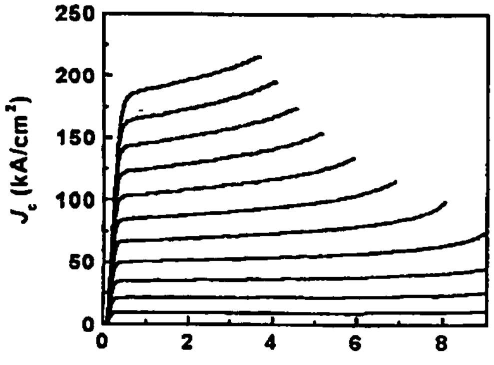

Fig. 6 Common-emitter curves of an InP/GaAsSb/InAlAs HBT showing the absence of collector current blocking and good breakdown characteristics.

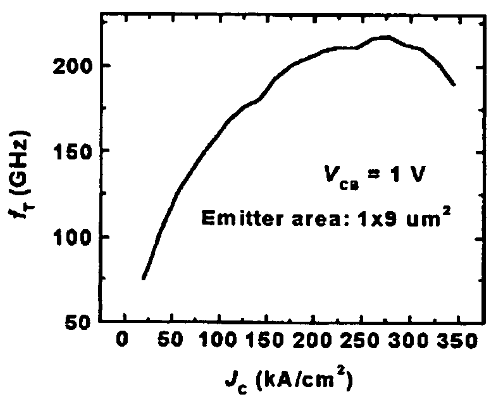

Fig. 7 f_T as a function of current density.

inter-metal dielectric is polyimide or bisbenzocyclobutene. Fig. 6 shows the common-emitter current characteristic for 1.4 × 2 μm² InP/GaAsSb/InAlAs DHBT, showing the absence of collector current blocking and good breakdown characteristics. The collector and base current ideality factors are 1.04 and 1.14, respectively, indicating high-quality emitter/base and collector/base heterojunctions. Typical transistors have a current gain of 40–50, breakdown voltages BV_{CEO} of 7–10 V and BV_{CBO} of 8–15 V, and a turn-on voltage V_{BEO} of 0.46 V at 1 A/cm². Microwave measurements performed on devices with a 1 × 9 μm² InP emitter show a current gain cutoff frequency f_T of over 210 GHz (Fig. 7). ICs composed of up to several hundred transistors were fabricated by Agilent's Microwave Technology Center and demonstrated excellent performance: ring oscillators with gate delay as low as 2.7 ps and static dividers operating up to 70 GHz were obtained.

IV. Summary

We have grown high-quality InP/GaAsSb heterojunction bipolar transistors (HBTs) for high-frequency applications by metalorganic vapor phase epitaxy (MOVPE) and gas-source molecular beam epitaxy (GSMBE) using carbon as a base dopant. Hole concentrations above 10^{20} cm^{-3} are achieved in a carbon-doped GaAsSb base layer with no measurable hydrogen passivation. In the case of MOVPE, CBr_4 doping results in strong interplay between doping level, growth rate, and layer composition in GaAsSb. InP/GaAsSb/InAlAs and GaAsSb/InP SLs show strong type I and type II luminescence, respectively, and are used to evaluate quickly the HBT's GaAsSb base layer and collector-base and base-emitter heterojunction quality. The HBTs exhibit excellent DC characteristics and a current gain cutoff frequency over 210 GHz.

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